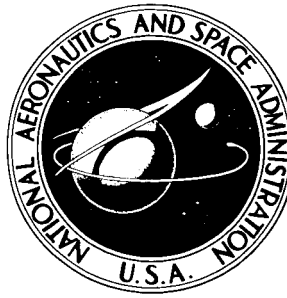


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# MINIMAL ENERGY BALLISTIC TRAJECTORIES FOR MANNED AND UNMANNED MISSIONS TO MERCURY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

Minimal-energy trajectories are determined for three Mercury missions: unmanned flybys, unmanned orbiters, and manned stopovers. The velocity requirements for these missions are assessed from consideration of three trajectory modes: direct transfers, unpowered Venus swingby transfers, and modified pericenter Venus swingby transfers. The total and incremental propulsive velocity requirements, the mission durations, and Earth entry velocities, where applicable, are investigated for all missions.

The missions have three distinct energy levels. The unmanned flyby mission has a minimum  $\Delta V$  of 4.2 km/sec, and the unmanned orbiter mission a minimum  $\Delta V$  of 11.2 km/sec. These requirements are in the same range as those for unmanned Mars probes and manned Mars stopovers, respectively. The manned Mercury stopovers have a minimum  $\Delta V$  requirement of 18.2 km/sec with a corresponding stay time of 174 days and mission duration of 414 days.

In addition to the minimal energy trajectory data discussed, data are presented on typical launch windows and communication distances for the missions of interest. Launch windows of 20 days are shown to exist at Earth for penalties of less than 5 percent of the total  $\Delta V$ . Maximum communication distances of about 1.5 AU are determined by the Earth-Mercury geometry rather than the transfer trajectory mode.

INTRODUCTION

Much work has been done to assess the mission requirements for exploration of the nearest planets, Mars and Venus. In the future, other planets of the solar system may receive increasing attention. Among these is Mercury, which is of interest if for no other reason than its close proximity to the Sun.

Missions to Mercury have been the subject of previous analyses (refs. 1-4). However, these analyses have emphasized a particular mission or trajectory mode. This report summarizes the results of a comprehensive study of trajectories between Earth and Mercury for the 1980-1999 period. The trajectory data presented provide a source from which specific trajectories of interest can be pinpointed and preliminary analysis of the overall mission requirements and subsystem integration can be initiated for a variety of missions.

The report defines the characteristics of the basic trajectories for both unmanned (one-way flyby and orbiter missions) and manned (round trip with stopover) missions to Mercury. Three modes of transfer trajectories (direct, unpowered Venus swingby, and modified pericenter Venus swingby) were considered, and a comparison was made of the performance (as measured by the propulsive velocity requirements -  $\Delta V$ , trip time, and entry velocity) of each mode for unmanned flybys, unmanned orbiters, and manned stopovers. In addition, an assessment has been made of the launch windows, the communication distance, and the solar radius time histories associated with missions representative of the 1980-1999 time period.

## SYMBOLS

HBEV	hyperbolic excess velocity, km/sec
V	velocity relative to planet, km/sec
$\Delta V$	$(HBEV^2 + V_e^2)^{1/2} - V_c$ , km/sec

## Subscripts

c	circular
e	escape
E	entry
T	total
$\text{♁}, \text{♀}, \text{♁}$	Mercury, Venus, Earth, respectively

## ANALYSIS

### Planet Motion

The motion of the planets was computed from two-body equations of motion with planet parameters as listed in the appendix. The data represent present knowledge and were compiled from references 1-6.

### Trajectory Mode Definition

Three modes of transfer trajectories were considered: the direct trip, the unpowered Venus swingby, and the modified pericenter Venus swingby. These modes are illustrated in figure 1. The direct and unpowered Venus swingby modes have the standard definitions. In many cases, the unpowered

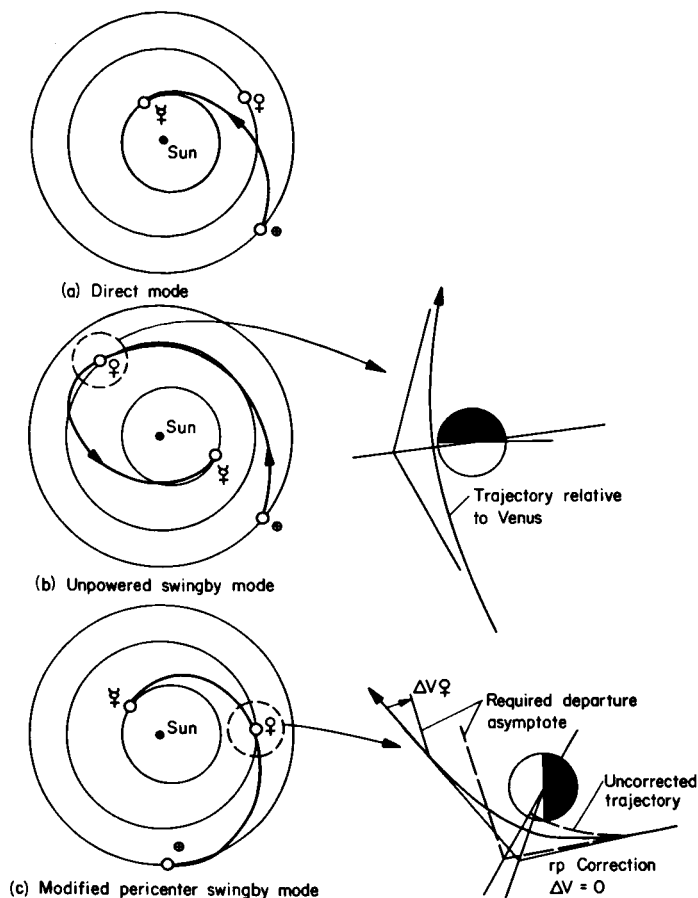


Figure 1.- Transfer trajectory geometry.

velocity are changed by corrections near Venus. Results of studies of this mode for Mars missions (ref. 5) have not displayed any advantages over the unpowered swingby modes. Preliminary calculations for the present study generally support a similar conclusion for Mercury missions. Thus, this mode is not included in the report.

### Transfer Trajectory Computation

Patched conic techniques were utilized to compute the single plane transfer trajectories between planets. In this method, the space vehicle is assumed to be acted upon by only one central force field at a time. The details of this technique will not be described here as they are thoroughly documented elsewhere (e.g., ref. 6).

<sup>1</sup>A minimum pericenter altitude at Venus of 250 km was chosen, since, below that value, atmospheric effects must be considered.

swingby requires closest approach distances at Venus within the planet atmosphere and even below the planet surface. Introducing the modified pericenter swingby mode removes these difficulties and makes possible a wider range of swingby transfers. In this mode, a midcourse maneuver (requiring a very small  $\Delta V$ ) is made during planet approach to raise the pericenter altitude to a specified minimum value.<sup>1</sup> Of course, if the standard swingby mode passes the planet above the minimum altitude, there is no need to use the modified pericenter swingby mode. The midcourse correction results in a planet departure at the proper hyperbolic excess speed for completion of the mission but on an asymptote of incorrect direction. A second correction of significant magnitude is made during the departure phase to rotate the direction without changing the velocity magnitude.

A more general powered swingby mode can be defined in which both the direction and the magnitude of the departure

Multiple plane transfers were not considered in this study. When the central angle is near  $180^\circ$  the multiple plane transfer requires less  $\Delta V$  than the single plane transfer. However, it does not result in  $\Delta V$  requirements lower than the minima available with the single plane transfer.

### Transfer Trajectory Constraints

The trajectories and corresponding requirements were computed for transfer from Earth orbit to Mercury orbit. At Earth, a circular orbit at sea level was assumed. The resulting injection velocity increments are representative of injection from near Earth orbits. If the orbit altitude were changed to 250 km, the Earth departure velocity increment ( $\Delta V_\oplus$ ) would decrease about 2 percent from the values shown herein. For orbiter missions a 1000 km altitude circular orbit at Mercury ( $V_e = 3.5$  km/sec and  $V_c = 2.5$  km/sec) was assumed as representative of nondecaying orbits.<sup>2</sup> Because of the size of Mercury, the Mercury arrival and departure velocity increments ( $\Delta V_\gamma$ ) shown would be decreased about 3 percent if a circular orbit at surface level were used. Eccentric orbits at Earth or Mercury would also reduce the  $\Delta V$  requirements below those shown, but such orbits were not considered in this study.

### RESULTS AND DISCUSSION

For a particular trajectory mode and mission, transfer trajectories and the corresponding  $\Delta V$  requirements can be computed as a function of two parameters, for example, launch date and trip time. For each launch date, there is a trip time that requires the lowest  $\Delta V$ . Plotting these minimum  $\Delta V$  requirements versus launch date yields a curve with several local minima, or launch opportunities, during a year, and the lowest of the local minima defines the minimum  $\Delta V$  transfer trajectory of the year.

Launch opportunities were analyzed to define the minimal energy trajectories for both the unmanned flyby mission ( $\Delta V_\oplus$  is minimized) and the unmanned orbiter mission ( $\Delta V_T = \Delta V_\oplus + \Delta V_\gamma$  is minimized). The results of the unmanned orbiter study formed the basis for the analysis of the manned stopover mission, where the sum of the total outbound  $\Delta V$  and the return  $\Delta V$  was minimized.

All mission modes are studied for the 1980-1999 A.D. time period. The three trajectory modes previously described (see fig. 1) are investigated in the performance of each mission mode.

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<sup>2</sup>A sensible atmosphere at least 400 km has been postulated by D. N. Vachon, General Electric Missiles and Space Division.

## Unmanned Missions

Direct flybys.- The pertinent Earth-Mercury geometry repeats itself every 4750 days (13 Earth years) so that the direct mode trajectory trip times and corresponding  $\Delta V$  requirements have a 13-year cycle. An apparent 6-7 year cycle also exists, but is much less exact than the 13-year period. Thus, the direct trip data contained in this report can also be used to define  $\Delta V$  requirements in other time periods of interest.

As with direct trips to Mars or Venus, launch opportunities for low energy Mercury missions occur in the vicinity of the Earth-Mercury closest approach. The closest approach is known as inferior conjunction for Venus and Mercury and as opposition for Mars and the outer planets. The relative motion of Mercury and Earth results in about three inferior conjunctions per year. Near an inferior conjunction, a local  $\Delta V$  minimum and corresponding launch opportunity exist.

Of the three opportunities each year, one opportunity displays the lowest Earth departure  $\Delta V$  for that year. These yearly minima are listed in table I for a 13-year cycle. The lower bound on the  $\Delta V_{\oplus}$  requirement for direct transfers is 4.8 km/sec with a trip time of 115 days for a Hohmann transfer in the plane of the ecliptic to Mercury's aphelion radius. The trajectories corresponding to table I arrive in the aphelion-descending node region and their requirements are close to those of the Hohmann transfer. The larger  $\Delta V$  is due to the inclination of Mercury's orbit to the ecliptic plane.

The trajectories shown arrive at Mercury with hyperbolic excess velocities on the order of 13 km/sec. If on-board experiments require lower excess velocities, the  $\Delta V$  at Earth departure must be increased. For example, the excess velocity can be reduced to 8 km/sec by utilizing a  $\Delta V_{\oplus}$  of 7 km/sec.

Direct orbiters.- The results for minimum-energy<sup>3</sup> Mercury orbiter missions are presented in table II for a 13-year cycle starting in 1980. The table illustrates two trends. First, one opportunity each year produces the lowest velocity requirement to achieve orbit about Mercury. The other opportunities usually require significantly higher energy levels. Secondly, as previously stated, one opportunity each year has the lowest Earth-departure  $\Delta V$  requirement with the others usually at much higher levels. These two opportunities always differ.

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<sup>3</sup>Throughout this report the phrase "minimum energy" refers to a minimized total velocity increment. While this is representative of the trajectory for the minimum mass in Earth orbit, it is not the identical mission since system mass requirements may depend upon parameters other than  $\Delta V$ .

Figure 2 shows the minimum total velocity increments for each year from 1980 to 1995. The total velocity increment ( $\Delta V_T = \Delta V_\oplus + \Delta V_\odot$ ) is seen to display a cyclic variation with about a 6-1/2-year period. The lowest energy trip has a  $\Delta V_T$  of 12.9 km/sec.

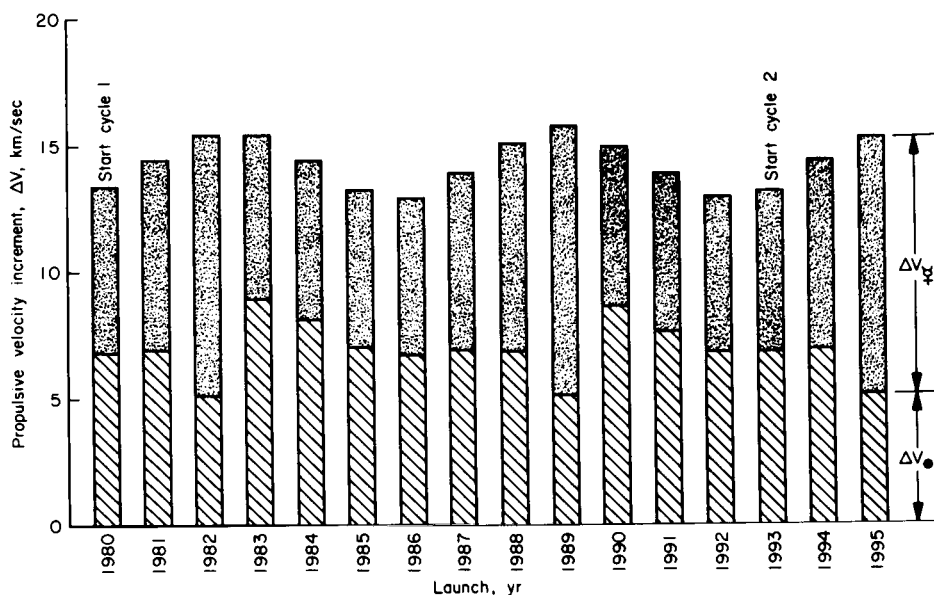


Figure 2.- Minimum  $\Delta V$  vs launch year; unmanned mercury orbiter mission; direct transfer.

A plot of the  $\Delta V$  requirements from table II as a function of Mercury's longitude at arrival is given in figure 3. This plot shows the importance

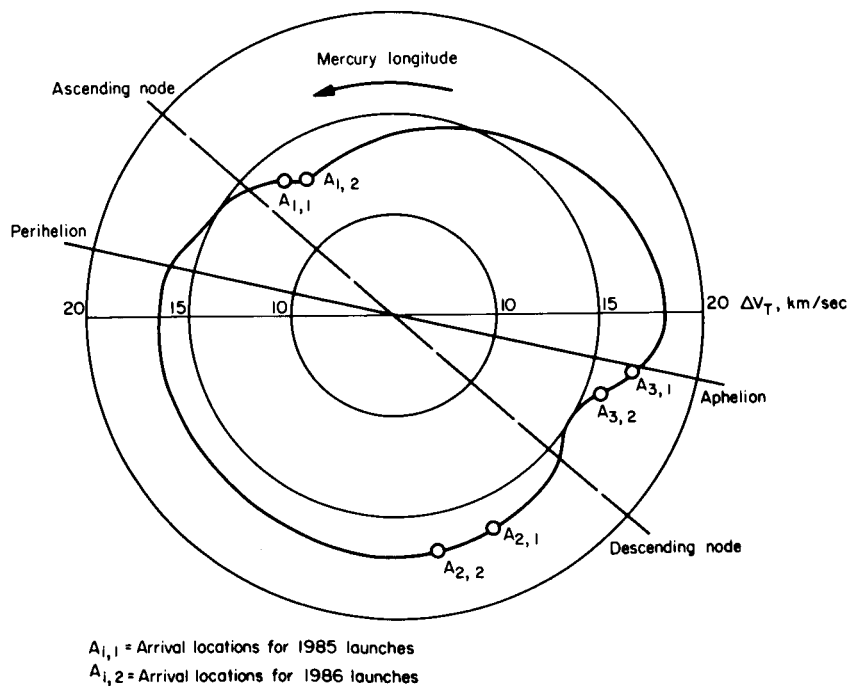


Figure 3.- Effect of arrival longitude on outbound  $\Delta V$  requirements; unmanned orbiter mission; direct transfer.

of Mercury's nodal points on the trajectory results; the regions of minimum  $\Delta V$  requirements occur near the nodes where the inclination of the transfer orbit to the ecliptic plane is a minimum. Since the orbit of Mercury has a large inclination ( $7^\circ$ ), the minima are quite definite. Of the two nodal regions, the ascending node requires the lowest  $\Delta V$ . Perihelion occurs near the ascending node and the corresponding higher heliocentric velocity of Mercury significantly reduces the relative velocity of the spacecraft at arrival and therefore reduces the required  $\Delta V_0$ .

The sequential arrival locations of the opportunities for 1985-1986 are shown in figure 3. The locations follow Mercury around its orbit of the Sun and are spaced about  $1-1/3$  Mercury periods apart. From year to year, the arrival locations move clockwise around Mercury's orbit (e.g.,  $A_{1,1}, A_{1,2}$ )<sup>4</sup> so that after 4750 days (13 years) point  $A_{1,14}$  will correspond to  $A_{1,1}, A_{2,14}$  to  $A_{2,1}$ , and  $A_{3,14}$  to  $A_{3,1}$ . The curve connects discrete points and indicates the approximate  $\Delta V_T$  with a very small error.

Unpowered Venus swingby. - Analysis of the Venus swingby trajectory mode showed that the minimum  $\Delta V$  trips for both unmanned missions (flyby and orbiter) occur for almost identical trajectories. Therefore, the two missions will be discussed together.

A Venus swingby to Mercury requires the coupling of two trajectories. The first is a successful Earth-Venus trajectory. Thus the swingby mode can be utilized only as frequently as opportunities for Earth-Venus trajectories occur. These occur every Earth-Venus conjunction (about every 17 months) and are plotted in reference 6. The second requirement is a Venus-Mercury trajectory in which Venus departure characteristics are defined by the previous arrival trajectory. The swingby trajectory analysis thus consists primarily of searching for Venus-Mercury trajectories which can be coupled (without a powered maneuver) with an Earth-Venus trajectory, to achieve the minimum  $\Delta V_T$  for the launch opportunity. The launch regions of interest were defined by means of the plots of reference 6. The entire swingby trajectory was then computed as an entity with the arrival and departure speeds at Venus matched to within 15 meters per second. This technique necessitates the computation of a large number of trajectories based on a parametric variation of trip time (both Earth-Venus and Venus-Mercury) and launch date. On the basis of selected comparisons with references 1-3, the data presented are felt to be representative of the minimum obtainable; however, every possible trajectory was not computed.

The  $\Delta V$  requirements for the minimum energy unpowered swingby transfers are given in table III and figure 4. For the flyby missions, the  $\Delta V_0$  can be interpreted in terms of hyperbolic excess speed at Mercury (i.e.,  $HBEV_0 = 9.4$  km/sec for 1980 and 11.8 km/sec for 1985). The flyby mission, using this trajectory mode, displays minimum Earth departure  $\Delta V$ 's which, in some cases, are 20 percent lower than the comparable direct trajectories.

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<sup>4</sup> $A_{i,j}$  where  $i$  =  $i$ th opportunity for given launch year;  
 $j$  =  $j$ th launch year beginning in 1985.

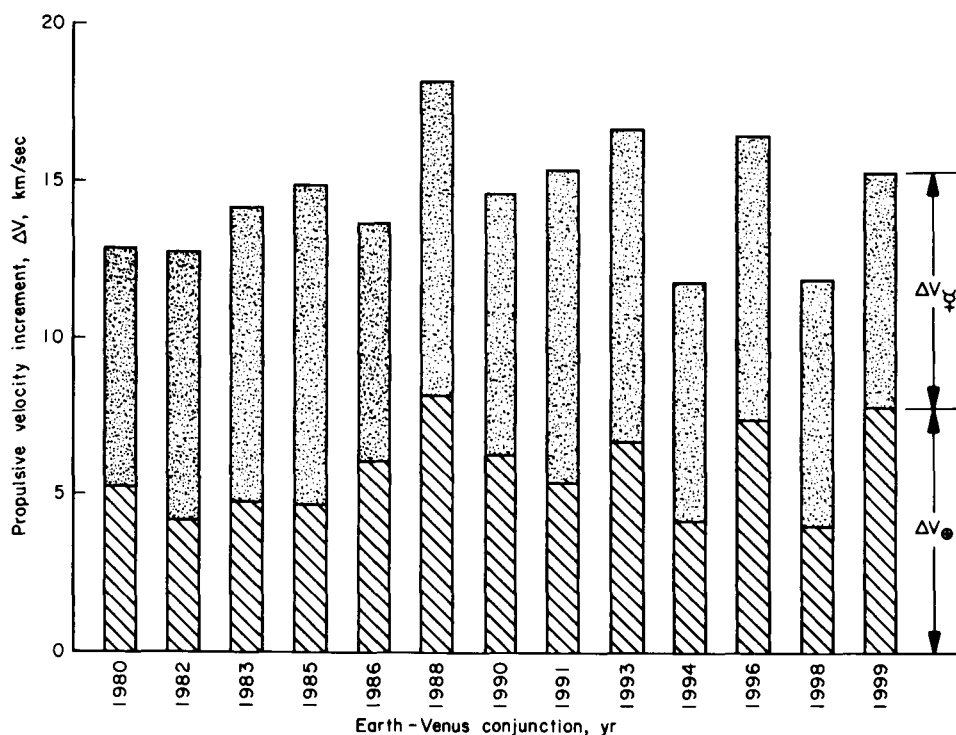


Figure 4. - Minimum  $\Delta V$  vs conjunction year; unmanned Mercury orbiter mission; unpowered Venus swingby transfer.

Two trends should be noted which are not directly evident in table III. First, the lowest  $\Delta V_T$  trips shown always depart Earth within 20 days of Earth-Venus inferior conjunction. The higher  $\Delta V_T$  trips depart progressively farther away. For these trips Venus-Mercury legs could not be found that would allow low energy Earth-Venus legs. Secondly, the arrival usually occurred near the descending node-aphelion region of Mercury's orbit. Consequently,  $\Delta V_0$  for the swingby trips is generally higher than that for the direct trips.<sup>†</sup> However, the Earth departure  $\Delta V$  is sufficiently low to provide several cases for which the total  $\Delta V$  is less than for the comparable direct trips, although a somewhat longer trip time is required.

Thus, while the Venus unpowered swingby mode does not always produce lower energy transfers, the requirements are lower in a sufficient number of cases to merit consideration of this mode in the analysis of Mercury missions. In fact, a comparison of tables I, II, and III indicates that over a 13-year cycle, the swingby mode produces transfers with energy requirements less than the lowest available from the direct mode.

Modified pericenter swingby. - The modified pericenter swingby mode enlarges the region of swingby opportunities since swingby transfers are now available in which the standard unpowered swingby trajectory would be required to pass Venus at altitudes below 250 km. Velocity requirements are presented in table IV and figure 5. Data are presented for only those opportunities which result in a lower Mercury orbiter  $\Delta V_T$  than is possible with the standard swingbys. Though modified pericenter swingbys exist during every

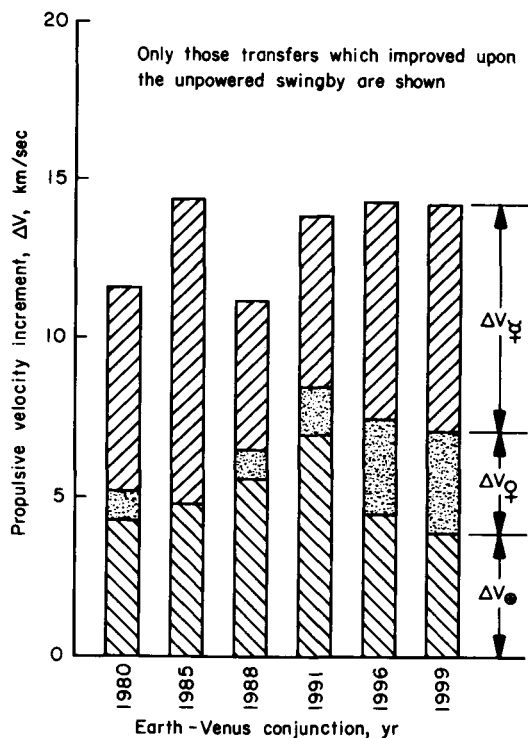


Figure 5.- Minimum  $\Delta V$  vs conjunction year; unmanned Mercury orbiter mission; modified pericenter Venus swingby transfer.

conjunction, the cases of interest tend to occur when the minimum energy unpowered swingby has a passage altitude close to the 250 km limit and when the mission velocity could have been reduced by allowing a lower altitude passage.

The velocity requirements for flyby missions using the modified pericenter swingby are always higher than those for the standard swingby since the  $\Delta V$  at Venus must be added to the Earth departure value. However, the Mercury arrival hyperbolic excess velocity can be equal to or less than those for the direct trips.

To this point, the minimum velocity requirements and associated trip times have been defined for the three trajectory modes for unmanned flyby and orbiter missions. It has been shown that the swingby trajectories achieve the lowest  $\Delta V$ 's for both missions.

#### Manned Missions

For round trip missions with minimum  $\Delta V$  requirements, one must obtain the minimum energy return leg transfer. Only the Mercury departure velocity increment ( $\Delta V_E$ ) is minimized since no constraint on Earth entry velocity has been imposed.<sup>†</sup> Combining these return transfers with suitable minimum energy outbound transfers (tables II, III, or IV) defines the minimum  $\Delta V_T$  round trip transfer. Each such combination has a specific stay time at Mercury associated with it.

The trajectory modes for the return leg are the same as those for the outbound leg. However, it will be seen that the return swingby trajectories of interest (those that reduce the total  $\Delta V$ ) typically increase the total mission length between 200 and 300 days, while the  $\Delta V_T$  reduction is less than 5 percent. Therefore, emphasis will be placed upon direct return legs; only typical data will be indicated for the swingbys.

The minimum  $\Delta V_E$  direct mode trajectory for each return opportunity is listed in table V for a 13-year cycle. The direct mode return is governed by the Earth-Mercury geometry which repeats every 4750 days (13 years). Figure 6 shows the required velocity increment for departure versus the departure longitude of Mercury. As with the arrival, the advantages of a departure near Mercury's ascending node-perihelion region are clear.

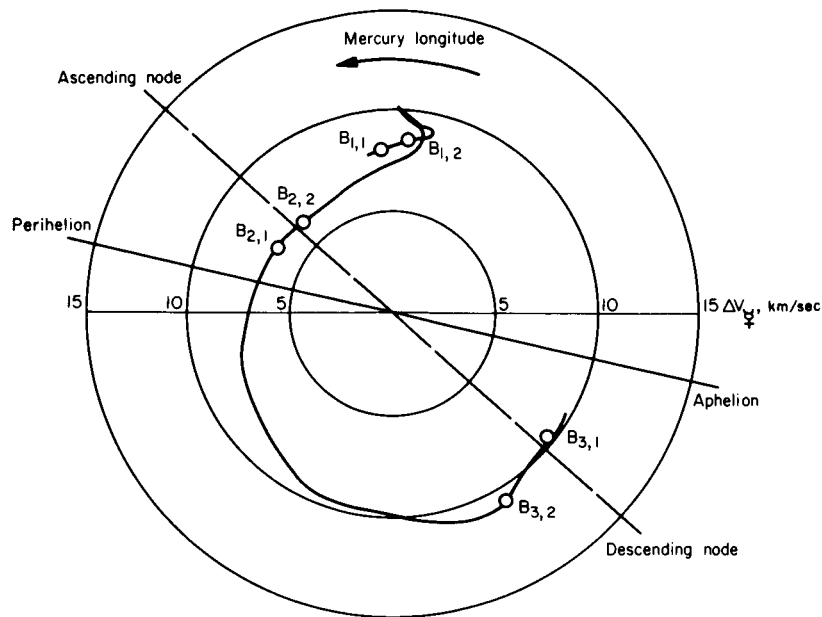


Figure 6. - Effect of departure longitude on  $\Delta V$  requirements; direct transfer; earth return.

The launch opportunities for a given Earth year ( $B_{1,1}$ ;  $B_{2,1}$ ;  $B_{3,1}$ ) move counterclockwise around Mercury's orbit and occur about every  $1\frac{1}{3}$  Mercury years. The opportunities for successive years move clockwise so that after 13 years the next opportunity ( $B_{1,14}$ )<sup>5</sup> coincides with  $B_{1,1}$  and so on. The line in the figure connects discrete points and thus is not continuous. The line indicates the approximate value with a very small error. The break in the curve occurs between the descending node and the region of maximum negative latitude. No minimum  $\Delta V$  departure occurred in that region.

Analysis of figure 6 shows two opportunities each year have low energy departures. One of these regions occurs near  $0^\circ$  longitude about  $40^\circ$  prior to the ascending node. The second region generally has a lower  $\Delta V$  and is around the ascending node just before the perihelion point is reached.

Table VI combines the data of tables II and V to define minimum energy round trip trajectories using two direct transfers. In each case an outbound leg from table II has been combined with the first low energy return leg from table V to depart after the Mercury arrival date of the outbound leg. Stay times at Mercury are of the order of one Mercury year, total trip times are approximately one Earth year, and the total  $\Delta V$  requirements range from 21 to 24 km/sec.

The available stay times at Mercury are restricted to multiples of the Mercury year (88 days) because both the arrival and departure for minimum energy transfers occur near the ascending node of Mercury. Shorter stay times would increase the  $\Delta V$  requirement. On the other hand, a review of table V

<sup>5</sup> $B_{1,j}$ ; where  $i$  =  $i$ th opportunity of given launch year;  
 $j$  =  $j$ th year from 1985.

shows that lower energy return legs can usually be obtained by waiting for the second return leg in table V to depart after the outbound leg Mercury arrival date. This would increase the associated stay time to about two Mercury years (176 days). Data for such round trips (utilizing the stay time associated with the optimum return leg) are presented in table VII and figure 7 for all yearly minimums between 1980 and 1999. It can be seen that the

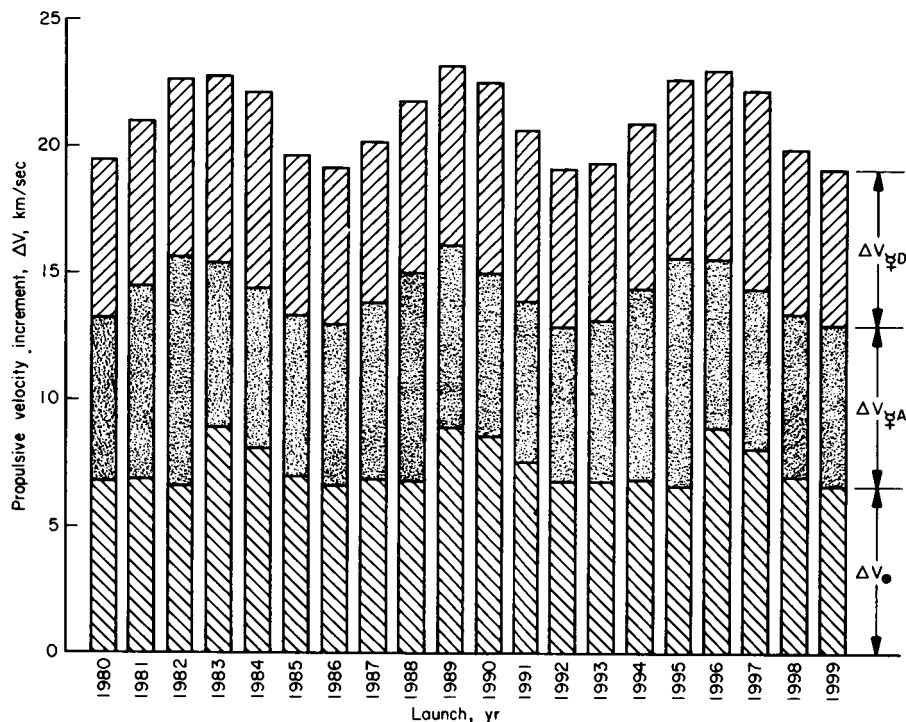


Figure 7.- Minimum  $\Delta V$  vs launch year for optimum stay time; manned mercury stopover missions; direct transfers.

minimum total  $\Delta V$  requirement is reduced to about 19 km/sec, while the total mission length is essentially unchanged because of the shorter return leg. However, in the total mission analysis and subsystem definition, the effect of the extra 90 days stopover on such items as radiation protection would have to be considered and trade-offs made to define the "best" trajectory. Figure 7 also shows the 6-7 year cycle exhibited by the direct leg missions.

Attention should be given here to the fact that the total  $\Delta V$  presented for the missions studied does not include any consideration of propulsive requirements for operations between the nominal orbital altitude of 1000 km and the surface of Mercury. Thus the  $\Delta V$ 's are somewhat low. However, the type and desirability of such operations have not yet been established.

It is of interest to investigate the possibilities of using combinations of Venus swingby and direct legs to lower the total  $\Delta V$  requirements further. Typical results of the investigation are delineated in tables VIII and IX for the years 1980 and 1983, respectively. Analysis of the tables reveals two trends. First, the use of an outbound swingby with a direct return leg tends to result in the minimum energy round trip; the velocity increment decreases a maximum of 1.2 km/sec below the corresponding direct trip of table VII.

Second, using a return swingby with any outbound trajectory mode shows no significant  $\Delta V$  savings and tends to greatly increase the mission duration.

The Earth entry speed is a parameter of interest in round trip missions and is listed in tables V-IX for all trajectories. For the trajectories of table VII, the minimum  $\Delta V_T$  direct mode missions, it varies over the range 14.5 to 17.4 km/sec. The lowest values occur for the missions with stay times of about two Mercury years. Minimum energy trajectories with stay times of one Mercury year (table VI) have entry velocities between 15.4 and 20.2 km/sec.

The results of the analysis of  $\Delta V_T$  requirements which has been described are summarized in figure 8. The figure presents the minimal  $\Delta V_T$

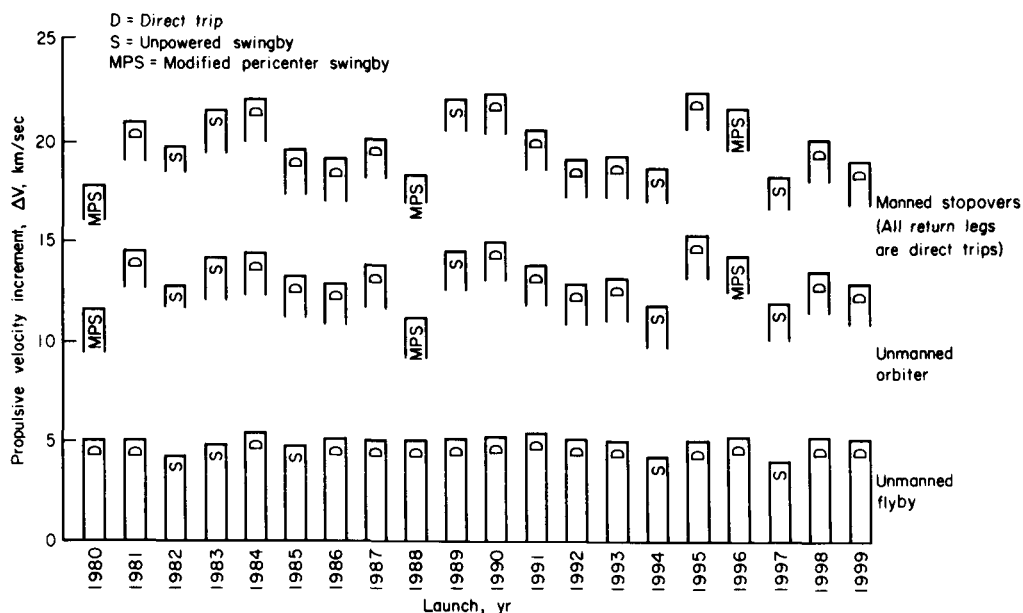


Figure 8.- Summary of minimum  $\Delta V$  missions, 1980-1999.

for each of the three missions studied as a function of the launch year. The particular trajectory mode which yields the minimum  $\Delta V_T$  is indicated on the figure. As can be seen, a swingby mode produces the lowest  $\Delta V_T$  requirement over the time period covered in figure 8. However, the low energy missions occur infrequently. If more frequent launch opportunities are desired, higher  $\Delta V$  requirements and the direct trip mode must be considered.

Up to this point, the minimum  $\Delta V_T$  requirements for missions to Mercury have been assessed without regard to other trajectory considerations, such as the launch window at Earth and Mercury or the communication distances involved. The rest of this report will consider typical examples of these effects.

## Launch Windows

Figure 9 shows the Earth departure velocity increments for launch near the launch date of the 1982 direct flyby (see table I). The dashed lines are

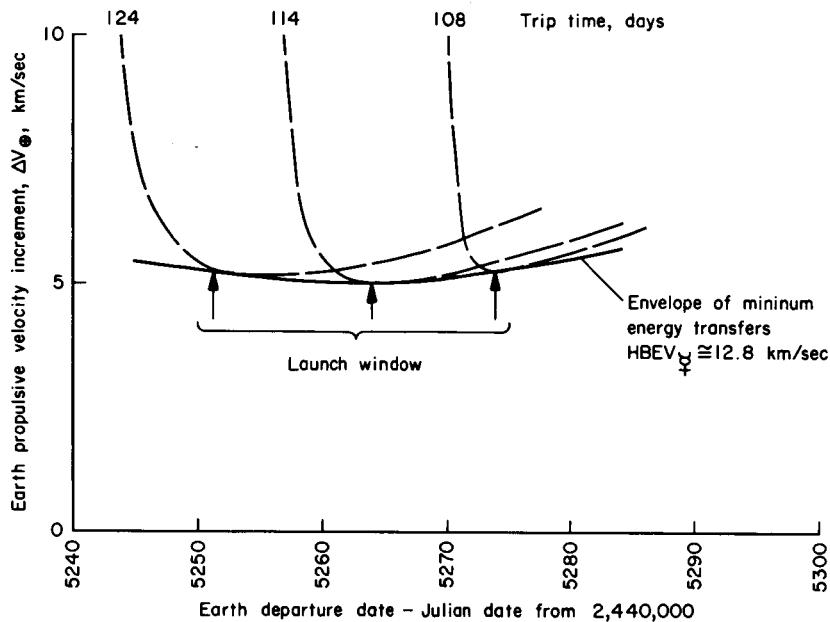


Figure 9.- Typical earth launch window; direct transfer; 1982 flyby mission.

constant trip times with central transfer angles greater than  $180^\circ$  and the solid line is the envelope of minimal energy transfers. The middle arrow locates the minimum departure  $\Delta V$  while the outer arrows indicate the region with  $\Delta V$  requirements within 5 percent of the minimum.<sup>6</sup>

The 5-percent value provides a 23-day window for Earth launch. It should be noted that all launches within this window arrive at Mercury on essentially the same date and with a hyperbolic excess velocity within 1 percent of 12.8 km/sec. A 30-day launch window would require a  $\Delta V$  increase of 8 percent (0.4 km/sec). Transfers of less than  $180^\circ$  exist, but the minimum values lie above the envelope shown.

The effect of small changes in the launch time around the launch date of the 1985 direct trip Mercury orbiter (see table II) is shown in figure 10. The Mercury arrival hyperbolic excess velocity and, therefore,  $\Delta V_T$ , corresponding to points on the envelope, increase rapidly away from the optimum launch date. The launch window is therefore smaller than for the flyby mission; the 5-percent  $\Delta V_T$  increase allows a 19-day window, while a 12-percent increase allows 30-day window.

<sup>6</sup>The 5-percent value was somewhat arbitrarily chosen. This value is approximately the penalty associated with a 30-day window for Mars missions.

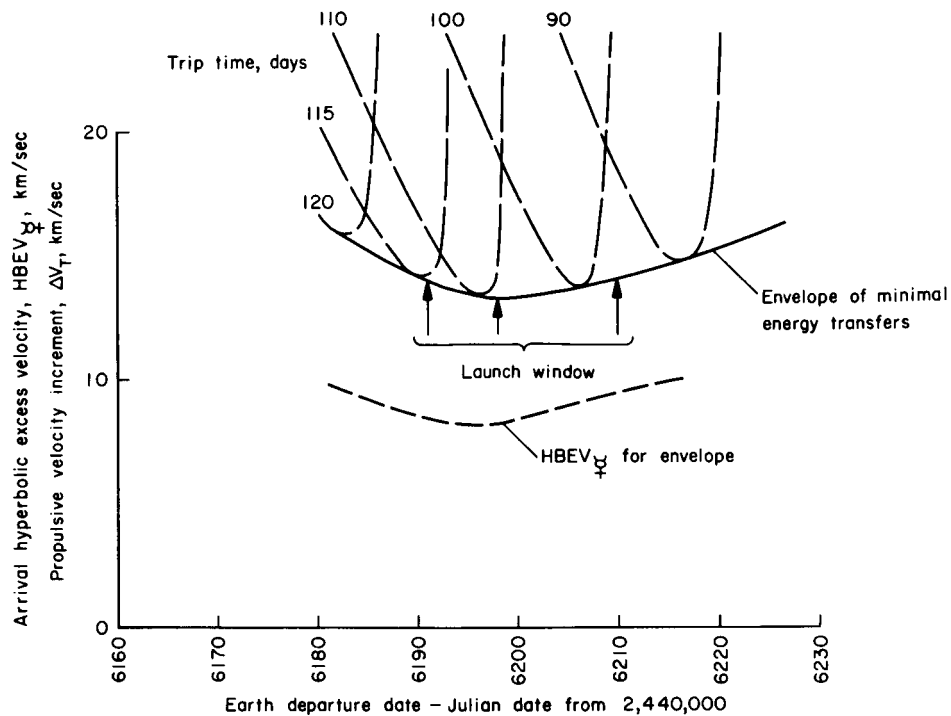
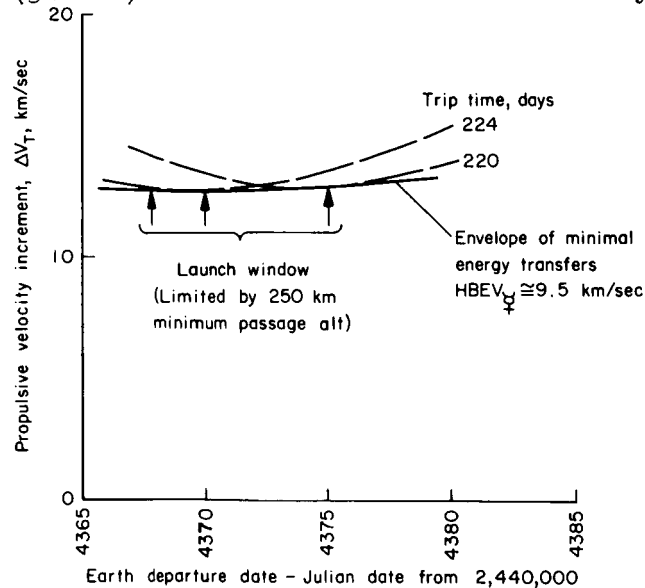


Figure 10.- Typical earth launch window; direct transfer; 1985 orbiter mission.

Launch windows for the orbiter mission using Venus swingby transfers are illustrated in figures 11(a), (b), and (c). Figure 11(a) corresponds to the 1980 conjunction unpowered swingby transfer (see table III). In this case, the Venus passage altitude for the minimum energy transfer is low (340 km) and the launch window is set by the minimum passage altitude constraint (250 km) rather than the 5-percent  $\Delta V_T$  allowance. The launch window is 7 days.

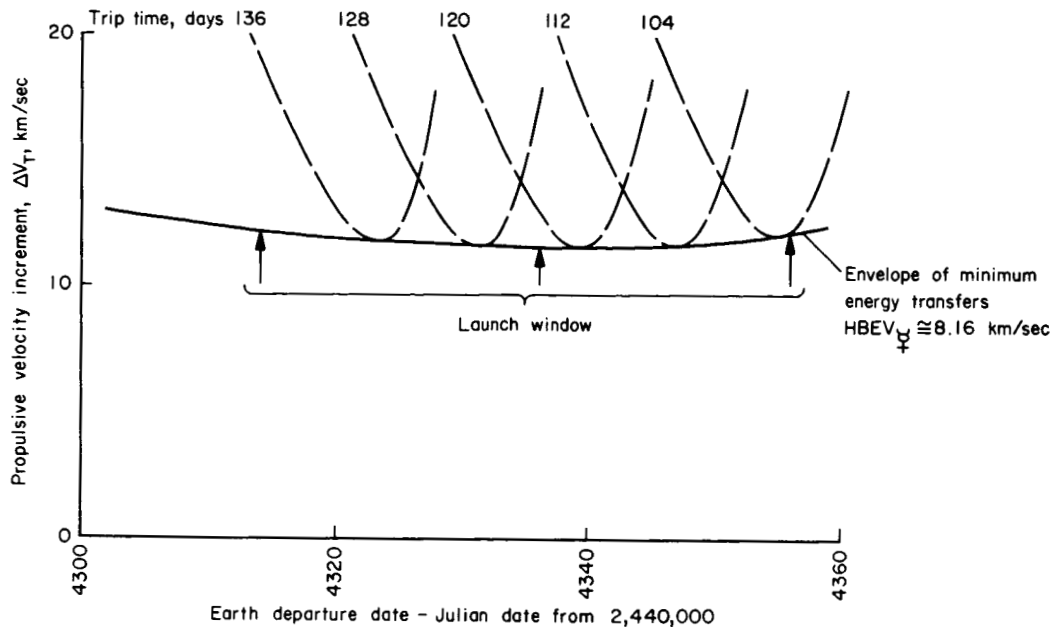


(a) Unpowered Venus swingby transfer; 1980 Mercury orbiter mission.

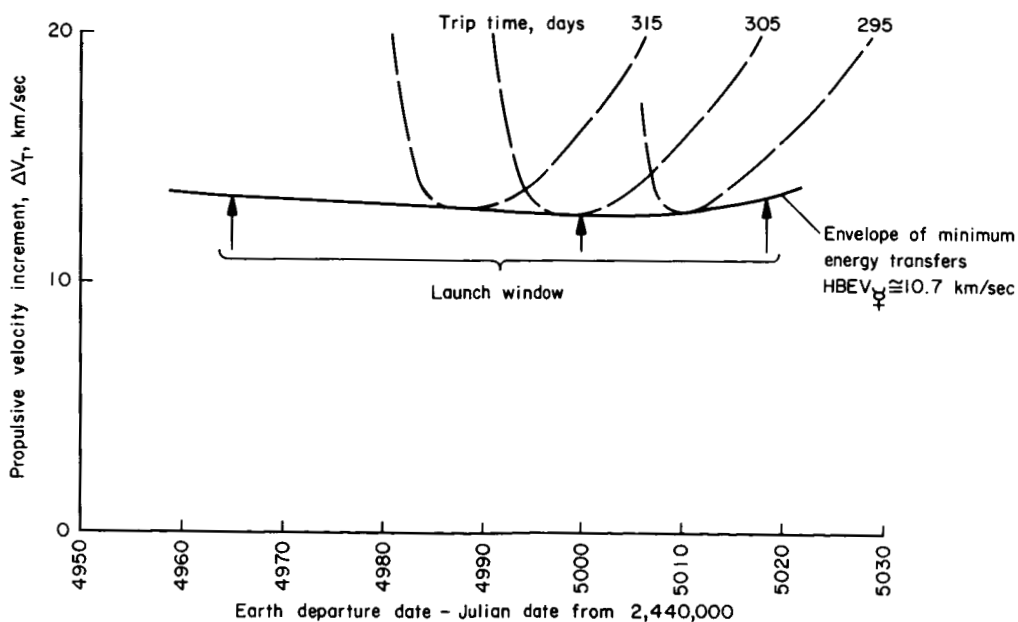
Figure 11.- Typical earth launch window.

When the unpowered swingby requires a low passage altitude at Venus, the modified pericenter swingby mode can usually be employed to advantage. This is shown in figure 11(b) which corresponds to the 1980 conjunction modified pericenter swingby transfer (see table IV). The launch window for the 5-percent  $\Delta V_T$  allowance is indicated in figure 11(b) by the outer arrows and is 42 days.

The 1982 conjunction for the unpowered Venus swingby transfer (see table III) is shown in figure 11(c). This conjunction is



(b) Modified pericenter Venus swingby transfer; 1980 Mercury orbiter mission.

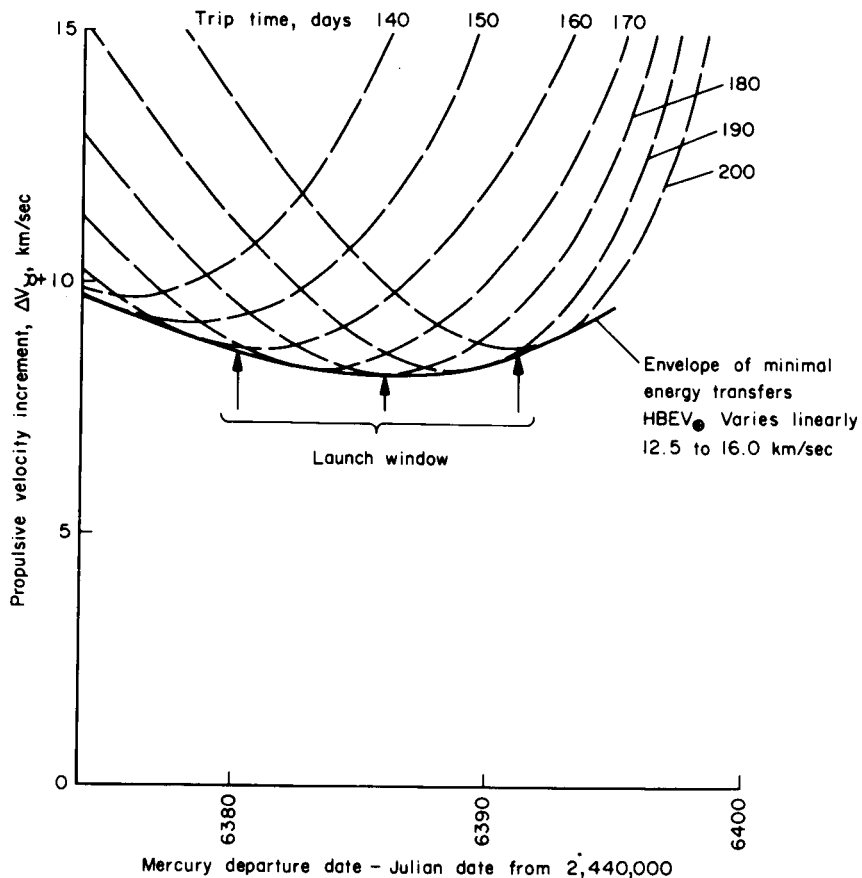


(c) Unpowered Venus swingby transfer; 1982 Mercury orbiter mission.

Figure 11.- Concluded.

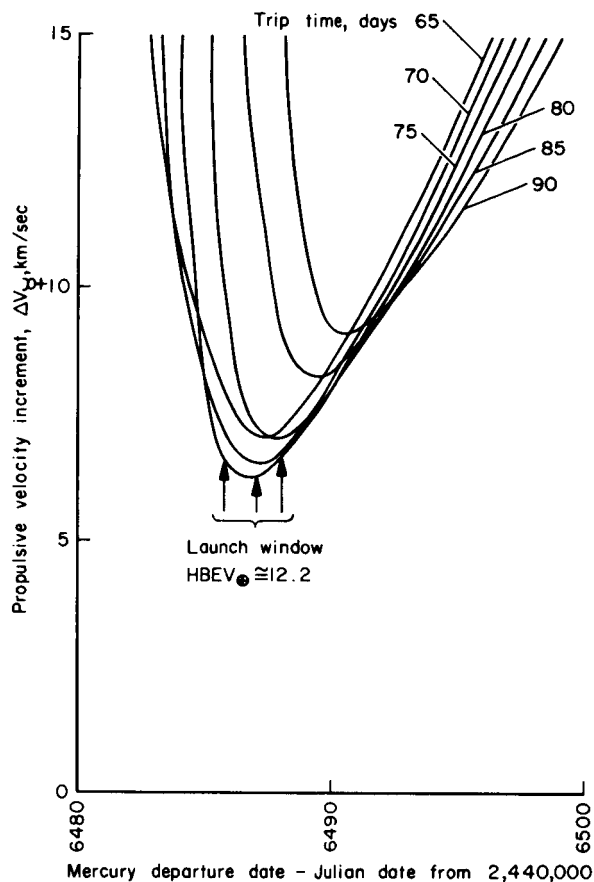
representative of a high passage altitude (1980 km). The launch window for a 5-percent  $\Delta V_T$  allowance is large (on the order of 50 days) and is usually limited at the later launch dates by the minimum Venus passage altitude constraint. The arrival hyperbolic excess velocity is approximately 10.7 km/sec and varies less than 1 percent during the launch window.

For the return leg, direct-mode minimum-energy transfer requires departure from one of two regions of Mercury's orbit as previously shown in tables VI and VII and figure 6. Departure after one Mercury year stay time (see table VI) generally yields a launch window at Mercury of 10 days for a 5-percent  $\Delta V_8$  increase. A typical case, corresponding to the first return opportunity in 1985 (see table V) is illustrated in figure 12(a). Departures after a 2-year stay time, while requiring lower  $\Delta V_8$ , yield smaller launch windows. Figure 12(b), which illustrates the second return opportunity of 1985 (see table V), indicates a 2-day window for a 5-percent  $\Delta V_8$  increase.



(a) Typical of one Mercury year stay time.

Figure 12.- Mercury launch window; direct transfer.

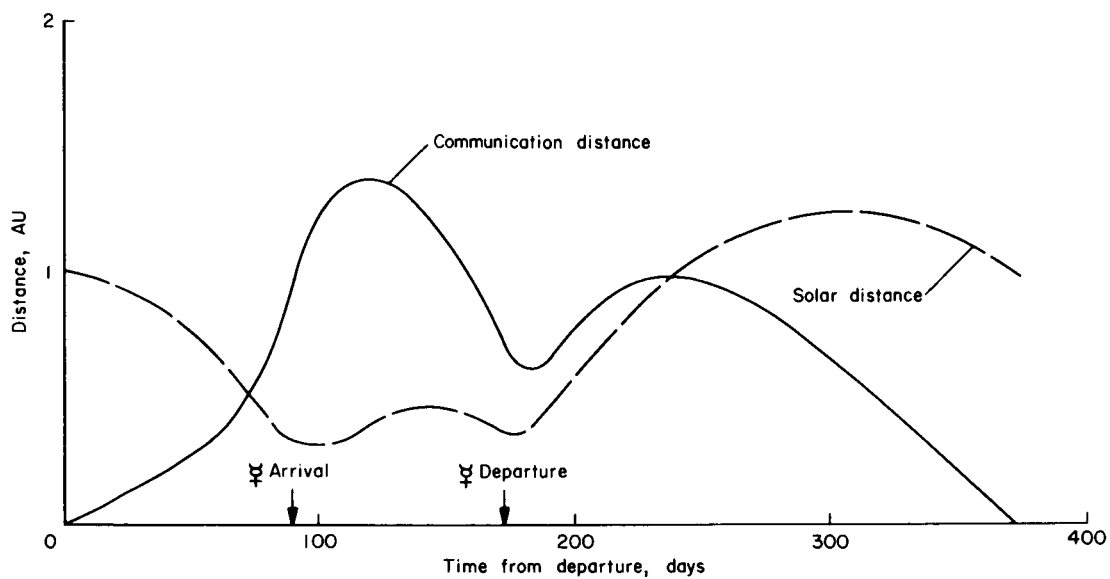


(b) Typical of two Mercury year stay time.

Figure 12.- Concluded.

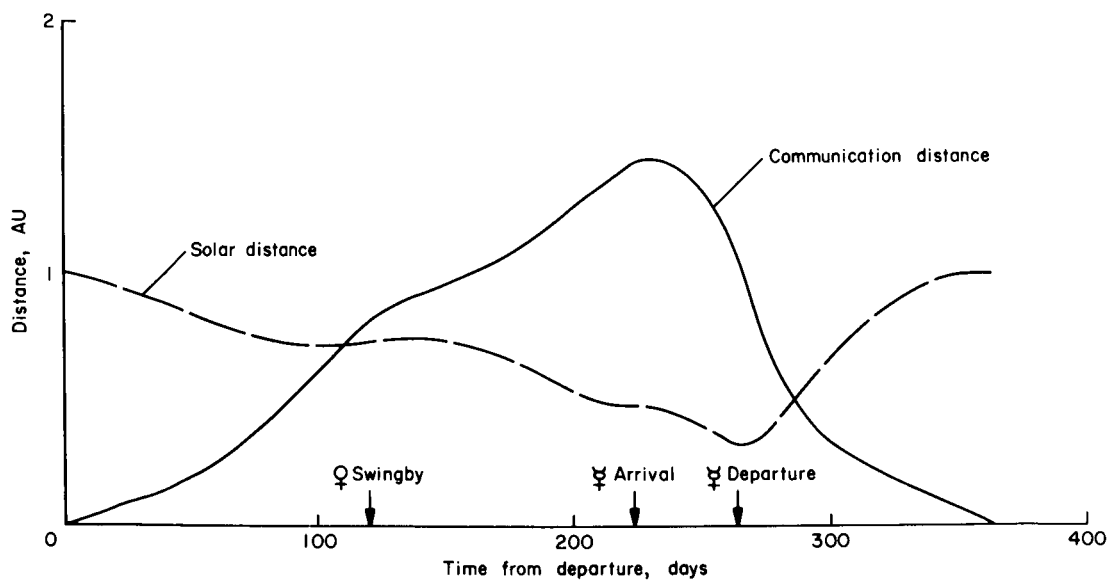
#### Communication and Solar Distances

Figures 13(a) - 13(c) are typical plots of communication distance and distance from the Sun during manned stopover missions. Comparison of the profiles reveals some of the trade-offs that must be made between the trajectory modes for complete mission analysis. For example, the swingby trajectories of figures 13(b) and 13(c) spend more time at distances greater than 1 AU from the Earth and within 0.5 AU of the Sun than does the direct trip. Therefore, although they have lower  $\Delta V_T$  requirements, they have greater communication and solar radiation protection requirements. It should also be noted that the maximum communication distance for these missions occurred during the stay at Mercury. In general, for all missions studied, the Earth-Mercury geometry controlled the maximum communication distance and also the closest solar approach.

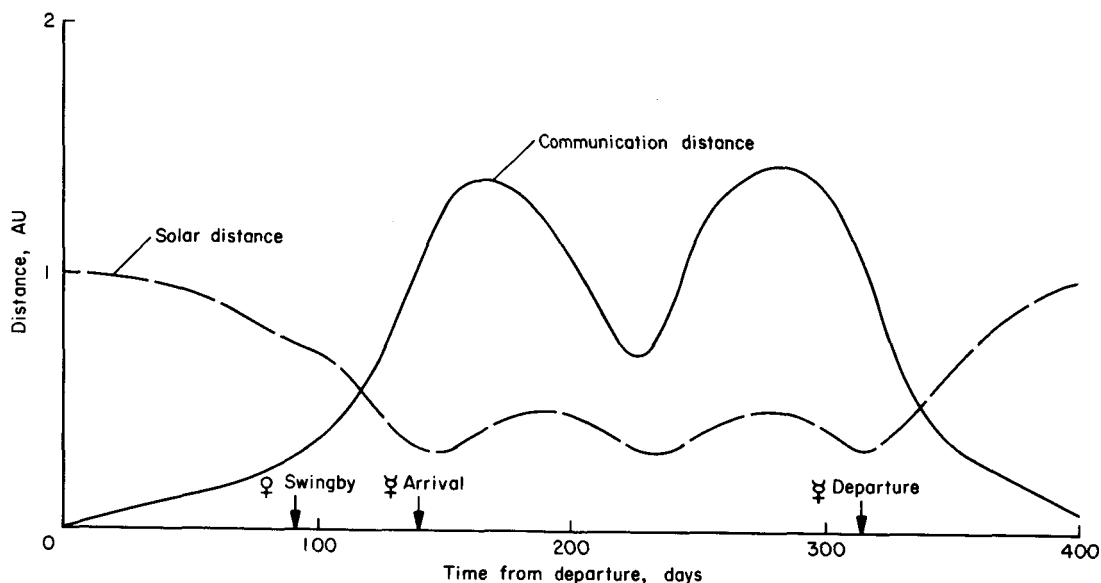


(a) Direct transfer both legs.

Figure 13.- Time history of communication and solar distance; 1980 Mercury stop over mission.



(b) Outbound unpowered Venus swingby with direct return.



(c) Outbound modified pericenter Venus swingby with direct return.

Figure 13.- Concluded.

#### CONCLUDING REMARKS

The analysis of the trajectory data has revealed some interesting points. Unmanned Mercury flybys can be performed almost any year for a  $\Delta V_{\oplus}$  about 5 km/sec. Specific years provide Venus swingby opportunities with a  $\Delta V_{\oplus}$  of about 4 km/sec. The direct trips require approximately 110 days while the swingby trips vary from 150 to 300 days. All of these low energy flybys pass Mercury near the aphelion-descending node region.

Because of the eccentricity and inclination of Mercury's orbit, all minimal energy unmanned orbiters arrive near the perihelion-ascending node region of Mercury's orbit. The trips of lowest energy are modified pericenter Venus swingbys and require a  $\Delta V_T$  of about 11.5 km/sec but occur only twice during the 20-year period studied. If the  $\Delta V_T$  requirement is allowed to increase to 15 km/sec and both direct trips and Venus swingbys are considered, then launch opportunities are available every year. The orbiter mission trip times vary from about 100 days for the direct trips to between 220 and 350 for the swingbys.

For the manned stopover missions, minimum energy trajectories both arrive and depart Mercury in the ascending node perihelion region. Thus, stay times are restricted to approximate multiples of Mercury's orbital period. A direct return leg was utilized since the return swingby modes greatly increased the mission duration with little reduction in the energy requirement. The total  $\Delta V$  requirement for the manned stopovers displayed a cyclic variation between 18.5 and 23 km/sec over a 6-7 year period.

Launch windows of 20 days can be achieved at Earth departure for less than a 5-percent total  $\Delta V$  penalty for all missions. However, a 5-percent  $\Delta V$  penalty at Mercury departure for the manned mission would allow Mercury departure windows of only 2 to 10 days.

Communication distances have a maximum on the order of 1.5 AU for all missions considered. Solar distances have a minimum of 0.31 AU.

National Aeronautics and Space Administration  
Moffett Field, Calif., Nov. 10, 1966  
130-06-04-03-21

# APPENDIX

## PLANETARY CONSTANTS

Parameter	Earth, ⊕	Venus, ♀	Mercury, ♿
Gravitational constant, $\mu$ , km <sup>3</sup> /sec <sup>2</sup>	3.99×10 <sup>5</sup>	3.26×10 <sup>5</sup>	2.17×10 <sup>4</sup>
Planet radius, r, km	6380	6100	2400
Surface escape velocity, V <sub>e</sub> , km/sec	11.2	10.3	4.3
Surface circular velocity, V <sub>c</sub> , km/sec	7.9	7.3	3.1
Eccentricity, e	0.0167	0.0068	0.2056
Orbit inclination, i, deg	0	3.4	7.0
Period of orbit, P, Earth days	365.255	224.7	87.96
Mean nodal longitude $\Omega$ , deg	0	76.3	47.8
Mean perihelion longitude $\omega$ , deg	102.3	131.0	76.8
Semimajor axis a, AU	1.0	0.723	0.387
Solar gravitational constant = 1.329×10 <sup>11</sup> km <sup>3</sup> /sec <sup>2</sup>			

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TABLE I.- MINIMUM  $\Delta V$  REQUIREMENT; UNMANNED MERCURY FLYBY MISSION;  
DIRECT TRANSFER

Launch year	Earth departure date*	$\Delta V_{\oplus}$ , km/sec	Trip time, days	HBEV $\phi$ , km/sec
1980	4570	5.0	105	15.2
1981	4912	5.0	114	13.8
1982	5264	5.0	114	12.8
1983	5614	5.2	116	13.0
1984	5964	5.4	115	13.2
1985	6422	5.2	105	16.7
1986	6776	5.1	100	15.9
1987	7116	5.0	110	15.1
1988	7464	5.0	114	12.7
1989	7814	5.1	114	13.0
1990	8166	5.2	114	13.1
1991	8512	5.5	116	13.2
1992	8974	5.1	102	16.7

\*All dates are Julian Date measured  
from 2440000 (5/23/68).

TABLE II.- MINIMUM  $\Delta V$  REQUIREMENT; UNMANNED MERCURY ORBITER MISSION;  
DIRECT TRANSFER

Launch year	Earth departure date	Trip time, days	$\Delta V_T$ , km/sec	$\Delta V_\oplus$ , km/sec	$\Delta V_\oplus$ , km/sec
1980	2440000+				
	4366	90	13.4	6.8	6.5
	4448	125	16.9	6.5	10.4
	4551	130	15.4	5.4	10.0
1981	4716	85	14.5	6.9	7.6
	4794	125	16.9	7.2	9.7
	4914	115	15.1	5.1	10.0
1982	5062	85	15.7	6.7	9.0
	5109	150	16.4	9.4	7.0
	5270	110	15.4	5.1	10.3
1983	5408	85	16.9	6.4	10.4
	5468	140	15.4	8.9	6.5
	5615	115	16.0	5.2	10.9
1984	5754	85	17.7	6.2	11.5
	5828	130	14.4	8.1	6.3
	5958	120	16.4	5.4	11.0
	6022	160	17.7	7.2	10.6
1985	6196	110	13.3	7.0	6.3
	6306	120	16.7	5.7	11.0
	6382	150	16.8	6.4	10.3
1986	6562	95	12.9	6.7	6.3
	6654	120	16.9	6.1	10.7
	6746	135	15.8	5.8	10.0
1987	6918	85	13.9	6.9	6.9
	7002	120	16.9	6.6	10.3
	7106	125	15.2	5.3	9.9
1988	7264	85	15.0	6.8	8.2
	7344	125	16.8	7.3	9.5
	7470	110	15.0	5.1	9.9
1989	7609	85	16.3	6.5	9.8
	7670	140	16.0	8.9	7.2
	7815	115	15.7	5.1	10.6
1990	7956	85	17.3	6.3	11.0
	8022	135	14.9	8.6	6.4
	8164	115	16.2	5.2	11.0
1991	8296	90	18.2	5.8	12.4
	8386	120	13.9	7.6	6.3
	8512	115	16.6	5.5	11.1
	8577	155	17.3	6.8	10.5
1992	8752	105	13.0	6.8	6.1
	8850	125	16.8	6.0	10.8
	8936	145	16.3	6.1	10.2

TABLE III. - MINIMUM  $\Delta V$  REQUIREMENTS; MERCURY FLYBY AND ORBITER MISSIONS;  
UNPOWERED VENUS SWINGBY TRANSFER

Conjunction year	Earth departure date	$\Delta V_{\oplus}$ , km/sec	Venus passage date	Pericenter altitude, km	Mercury arrival date	$\Delta V_{\odot}$ , km/sec	Total trip, days	$\Delta V_T$ , km/sec
1980	24400000+	5.3	24400000+	340	24400000+	7.6	224	12.9
1982	4370	4.2	4490	1980	4594	8.6	305	12.8
1983	5000	4.8	5168	270	5305	9.4	144	14.2
1985	5484	4.7	5569	1150	5628	10.2	270	14.9
1986	6210	6.1	6361	250	6480	7.6	136	13.7
1988	6634	8.2	6722	320	6770	10.0	435	18.2
1990	7160	6.3	7423	1190	7595	8.3	242	14.6
1991	7680	5.4	7865	300	7922	10.0	238	15.4
1993	8412	6.7	8556	2960	8650	10.0	235	16.7
1994	8840	4.2	9026	1360	9075	7.6	290	11.8
	9650		9824		9940			
1996	24500000+	7.4	24500000+	3420	24500000+	9.1	230	16.5
1998	0005	4.0	0192	3620	0235	7.9	290	11.9
1999	0810	7.8	0976	600	1100	7.5	190	15.3
	1210		1361		1400			

TABLE IV. - MINIMUM  $\Delta V$  REQUIREMENTS; UNMANNED MERCURY ORBITER MISSION; MODIFIED PERICENTER  
VENUS SWINGBY TRANSFER

Conjunction year	Earth departure date	$\Delta V_{\oplus}$ , km/sec	Venus passage date	Pericenter altitude, km	$\Delta V_{\odot}$ , km/sec	Mercury arrival date	$\Delta V_{\odot}$ , km/sec	Total trip, days	$\Delta V_T$ , km/sec
1980	24400000+	4.3	24400000+	250	0.9	24400000+	6.4	124	11.6
1985	4336	4.7	4412	250	.1	4460	9.6	260	14.4
1988	6200	5.6	6363	250	.9	6460	4.7	300	11.2
1991	7330	7.0	7519	250	1.5	7630	5.4	340	13.9
	8440		8657			8780			
1996	24500000+	4.5	24500000+	250	3.0	24500000+	6.8	210	14.3
1999	0180	3.9	0305	250	3.2	0390	7.1	230	14.2
	1310		1443			1540			

TABLE V.- MINIMUM  $\Delta V$  REQUIREMENTS; EARTH RETURN; DIRECT TRANSFER

Mercury departure date	Trip time, days	$\Delta V$ , km/sec	Earth entry velocity, km/sec
2440000+			
4538	200	8.7	19.2
4634	100	6.2	14.5
4754	80	10.8	14.3
4890	220	9.0	20.2
4984	115	6.5	14.8
5100	70	10.2	16.1
5242	235	9.3	20.9
5333	130	7.0	15.4
5446	65	9.2	17.6
5594	250	9.6	21.5
5684	150	7.4	16.5
5792	65	8.1	18.3
5946	265	9.8	22.1
6034	165	7.8	17.3
6138	65	7.2	18.8
6262	115	9.8	13.2
6388	185	8.2	18.6
6486	75	6.4	16.7
6611	135	9.8	14.2
6738	200	8.6	19.3
6834	90	6.2	15.0
6956	85	10.9	13.8
7088	210	8.9	19.7
7184	105	6.4	14.6
7302	75	10.5	15.1
7440	225	9.2	20.4
7532	125	6.8	15.2
7648	65	9.7	17.3
7794	245	9.5	21.4
7883	140	7.2	15.9
7994	65	8.7	17.9
8146	260	9.7	22.0
8234	155	7.6	16.8
8340	65	7.7	18.6
8498	275	9.9	22.4
8585	170	8.0	17.6
8688	70	6.8	17.4
8808	130	10.2	13.5
8936	185	8.4	18.4
9036	80	6.3	15.6
9162	140	9.9	14.2

TABLE VI.- MINIMUM  $\Delta V$  REQUIREMENT; STAY TIME < 1 MERCURY YEAR; MANNED MERCURY STOPOVER MISSION;  
DIRECT OUTBOUND AND RETURN TRANSFERS

Launch year	Earth departure date	$\Delta V_{\oplus}$ , km/sec	Trip time, days	$\Delta V_{\oplus}$ arrival, km/sec	Stay time, days	$\Delta V_{\oplus}$ departure, km/sec	Trip time, days	Earth entry velocity, km/sec	Total $\Delta V$ , km/sec	Mission length, days
	2440000+									
1980	4366	6.8	90	6.5	82	8.7	200	19.2	22.0	372
1981	4716	6.9	85	7.6	89	9.0	220	20.2	23.5	394
1982	5109	9.4	150	7.0	74	7.0	130	15.4	23.4	354
1983	5468	8.9	140	6.5	76	7.4	150	16.5	22.8	366
1984	5828	8.1	130	6.3	76	7.8	165	17.3	22.2	371
1985	6196	7.0	110	6.3	82	8.2	185	18.6	21.5	377
1986	6562	6.7	95	6.3	83	8.6	200	19.3	21.5	376
1987	6918	6.9	85	6.9	85	8.9	210	19.7	22.8	380
1988	7344	7.3	125	9.5	63	6.8	125	15.2	23.6	313
1989	7670	8.9	140	7.2	73	7.2	140	15.9	23.2	353
1990	8022	8.6	135	6.4	77	7.6	155	16.8	22.5	367
1991	8386	7.6	120	6.3	79	8.0	170	17.6	21.9	369
1992	8752	6.8	105	6.1	79	8.4	185	18.4	21.4	369
1993	9116	6.8	90	6.4	82	8.7	200	19.2	21.9	372
1994	9466	6.9	85	7.5	89	9.0	220	20.2	23.4	394
1995	9859	9.5	150	7.0	74	7.0	130	15.4	23.5	354
	2450000+									
1996	0218	8.9	140	6.7	75	7.4	145	16.2	23.0	360
1997	0578	8.1	130	6.3	77	7.8	165	17.4	22.2	372
1998	0946	7.0	110	6.5	79	8.2	175	17.9	21.7	364
1999	1312	6.6	95	6.3	81	8.5	195	19.0	21.4	371

TABLE VII.- MINIMUM  $\Delta V$  REQUIREMENT; OPTIMUM STAY TIME; MANNED MERCURY STOPOVER MISSION;  
DIRECT OUTBOUND AND RETURN TRANSFERS

Launch year	Earth departure date	$\Delta V_{\oplus}$ , km/sec	Trip time, days	$\Delta V_{\oplus}$ arrival, km/sec	Stay time, days	$\Delta V_{\oplus}$ departure, km/sec	Trip time, days	Earth entry velocity, km/sec	Total $\Delta V$ , km/sec	Mission length, days
1980	2440000+	6.8	90	6.5	178	6.2	100	14.5	19.5	368
1981	4366	6.9	85	7.6	183	6.5	115	14.8	21.0	383
1982	4716	6.7	85	9.0	186	7.0	130	15.4	22.7	401
1983	5062	8.9	140	6.5	76	7.4	150	16.5	22.8	366
1984	5468	8.1	130	6.3	76	7.8	165	17.3	22.2	371
1985	5828	7.0	110	6.3	180	6.4	75	16.7	19.7	365
1986	6196	6.7	95	6.3	177	6.2	90	15.0	19.2	362
1987	6562	6.9	85	6.9	181	6.4	105	14.6	20.2	371
1988	6918	6.8	85	8.2	183	6.8	125	15.2	21.8	393
1989	7264	8.9	140	7.2	73	7.2	140	15.9	23.2	353
1990	7670	8.6	135	6.4	77	7.6	155	16.8	22.5	367
1991	8022	7.6	120	6.3	182	6.8	70	17.4	20.7	372
1992	8386	6.8	105	6.1	179	6.3	80	15.6	19.2	364
1993	8752	6.8	90	6.4	178	6.2	100	14.5	19.4	368
1994	9116	6.9	85	7.5	183	6.5	115	14.8	20.9	383
1995	9466	6.7	85	8.9	186	7.0	130	15.4	22.6	401
	9812									
	2450000+									
1996	0218	8.9	140	6.7	75	7.4	145	16.2	23.0	360
1997	0578	8.1	130	6.3	77	7.8	165	17.4	22.2	372
1998	0946	7.0	110	6.5	180	6.4	75	16.8	19.9	365
1999	1312	6.6	95	6.3	177	6.2	90	14.9	19.1	362

TABLE VIII.- TRAJECTORY MODE COMPARISON: 1980 LAUNCH; MINIMUM  $\Delta V$  REQUIREMENT; MANNED MERCURY STOPOVER MISSION

Trip type <sup>1</sup> Item	D-D	S-D	MPS-D	D-S	S-S	MPS-S
Depart Earth	4366 <sup>2</sup>	4370	4336	4551	4370	4336
$\Delta V_{\oplus}$ (km/sec)	6.8	5.3	4.3	5.4	5.3	4.3
Pass Venus	--	4489	4412	--	4489	4412
Altitude (km)	--	346	250	--	346	250
$\Delta V_{\odot}$ (km/sec)	--	--	0.9	--	--	0.9
Arrive Mercury	4456	4594	4460	4681	4594	4460
$\Delta V_{\oplus}$ (km/sec)	6.5	7.6	6.4	10.0	7.6	6.4
Depart Mercury	4538	4634	4538	4704	4704	4704
$\Delta V_{\oplus}$ (km/sec)	8.7	6.2	8.7	6.2	6.2	6.2
Pass Venus	--	--	--	4820	4820	4820
Altitude (km)	--	--	--	355	355	355
Arrive Earth	4738	4734	4738	4970	4970	4970
$V_E$ (km/sec)	19.2	14.5	19.2	12.4	12.4	12.4
$\Delta V_T$ (km/sec)	22.0 (19.5) <sup>3</sup>	19.1	20.3 (17.8) <sup>3</sup>	22.2	19.1	17.9
Trip time (days)	372 (368)	364	418 (398)	419	600	634
Stay time (days)	82 (178)	40	78 (174)	23	110	244

<sup>1</sup>Outbound leg - inbound leg.

D = Direct

S = Venus swingby

MPS = Venus swingby with  $\Delta V$  to raise pericenter radius at passage

<sup>2</sup>All dates are Julian Date measured from 2440000.

<sup>3</sup>Numbers in brackets indicate result of using the 4634 Mercury departure on the D-D and MPS-D trips.

TABLE IX.- TRAJECTORY MODE COMPARISON: 1983 LAUNCH; MINIMUM  $\Delta V$  REQUIREMENT; MANNED MERCURY STOPOVER MISSION

Item	Trip type					
	D-D	S-D	D-S	D-MPS	S-S	S-MPS
Depart Earth	5468	5484	5615	5615	5484	5484
$\Delta V_{\oplus}$ (km/sec)	8.9	4.8	5.2	5.2	4.8	4.8
Pass Venus	--	5569	--	--	5569	5569
Altitude (km)	--	277	--	--	277	277
Arrive Mercury	5608	5628	5730	5730	5628	5628
$\Delta V_{\oplus}$ (km/sec)	6.5	9.4	10.9	10.9	9.4	9.4
Depart Mercury	5684	5684	5770	5860	5770	5860
$\Delta V_{\oplus}$ (km/sec)	7.4	7.4	8.7	5.5	8.7	5.5
Pass Venus	--	--	5979	5969	5979	5969
Altitude (km)	--	--	5460	250	5460	250
$\Delta V_{\oplus}$ (km/sec)	--	--	--	0.5	--	0.5
Arrive Earth	5834	5834	6200	6140	6200	6140
$V_E$ (km/sec)	16.5	16.5	18.2	12.4	18.2	12.4
$\Delta V_T$ (km/sec)	22.8	21.6	24.7	22.0	22.8	20.2
Trip time (days)	366	350	585	525	716	656
Stay time (days)	76	56	40	130	142	232

*"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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